Silicon mirrors – an asymmetric test mass configuration

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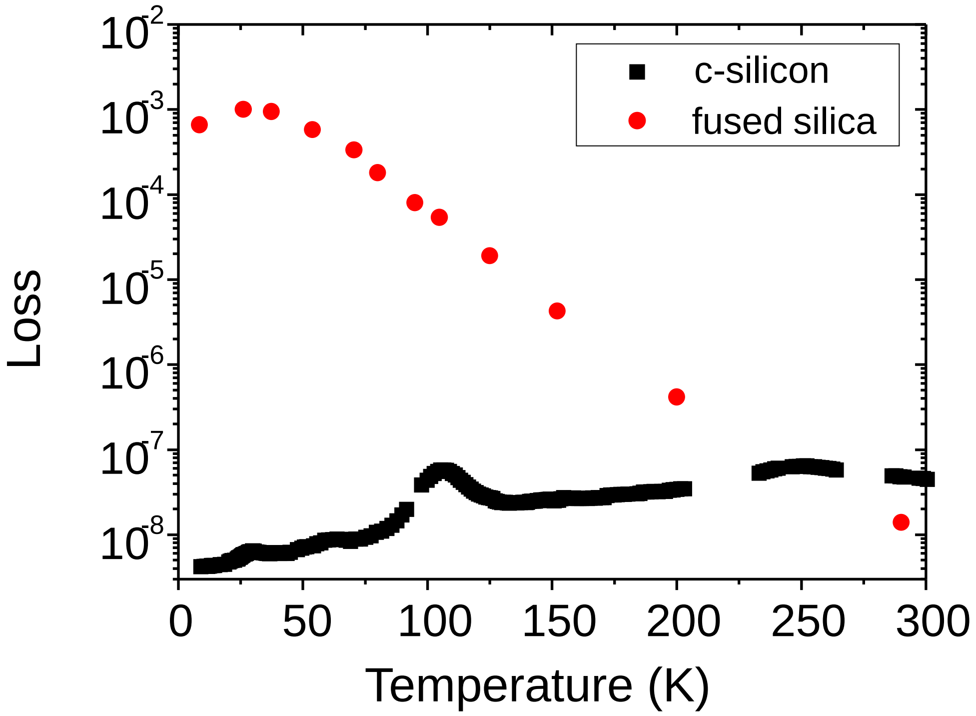
Overview

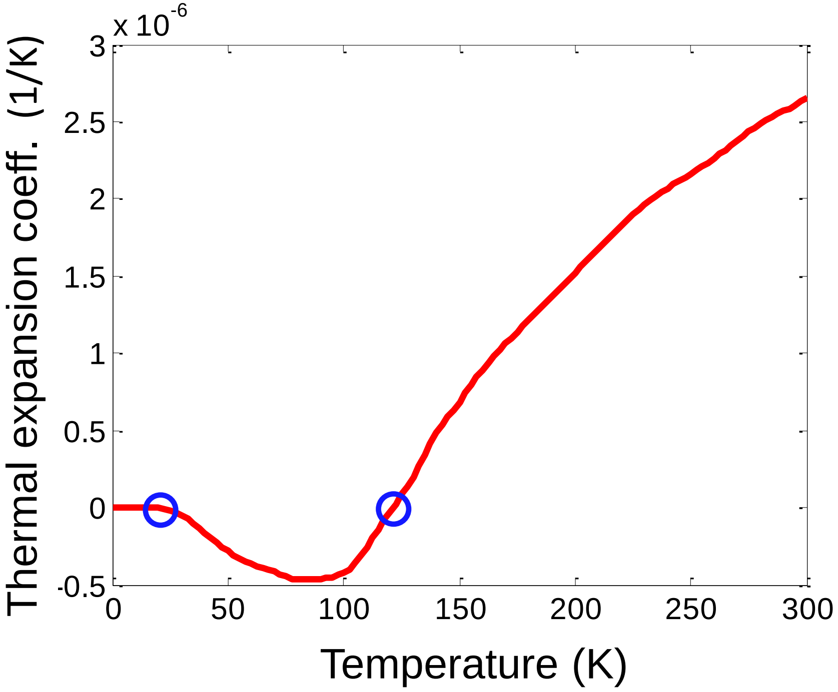
- Silicon as a test mass material
- Silicon – types, sizes and optical absorption
- Absorption tolerances of ITM and ETM
- Asymmetric test-mass configuration concept
- Implications for coating thermal noise

Silicon mirrors for GW detectors

- Silicon attractive due to low mechanical loss (low thermal noise), zeros in thermal expansion coefficient (low thermoelastic noise)



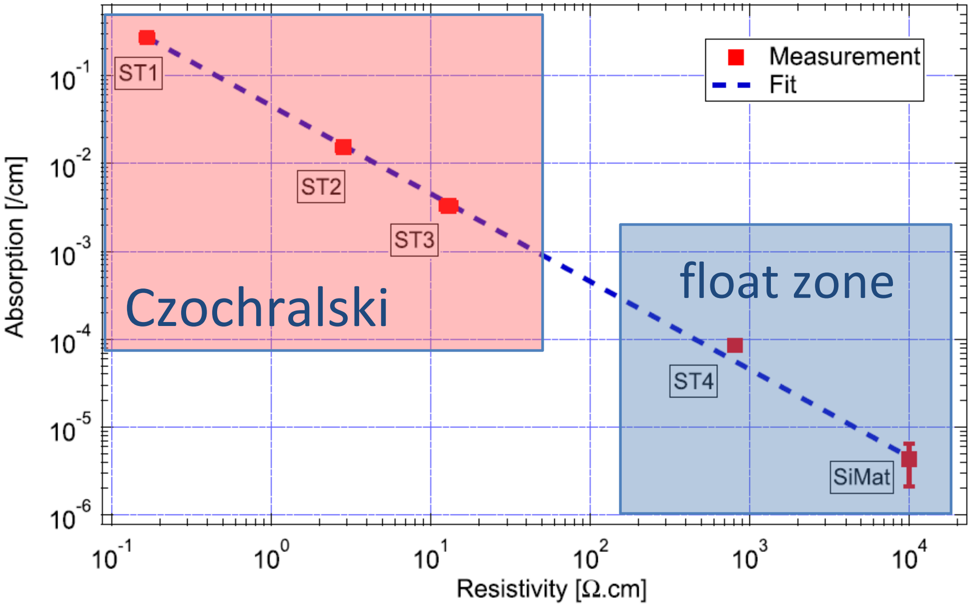
[This data – Schwarz et al., 2009]



[Touloukian 1970]

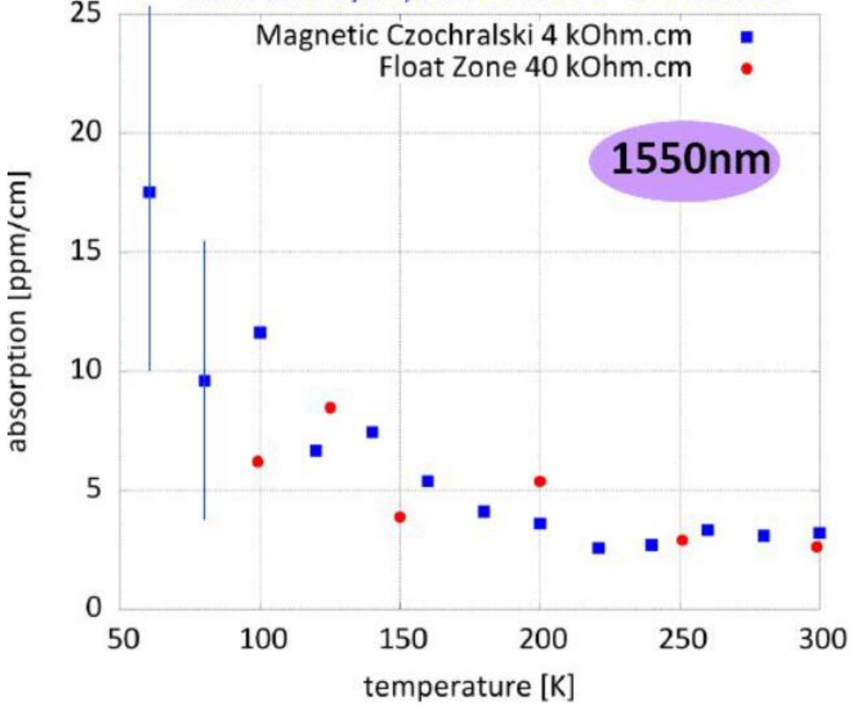
Silicon mirrors for GW detectors

- Float zone silicon with low levels of impurities can have low optical absorption – size (currently?) limited to ≈20 cm diamater
- Czochralski silicon avaialble in larger sizes, but tends to have higher absorption
- Magnetically purified Czochralski growth – can produce similar absorption to good float zone (but indications of large spatial variation), in principle can be made in sizes up to ≈ 40-45cm



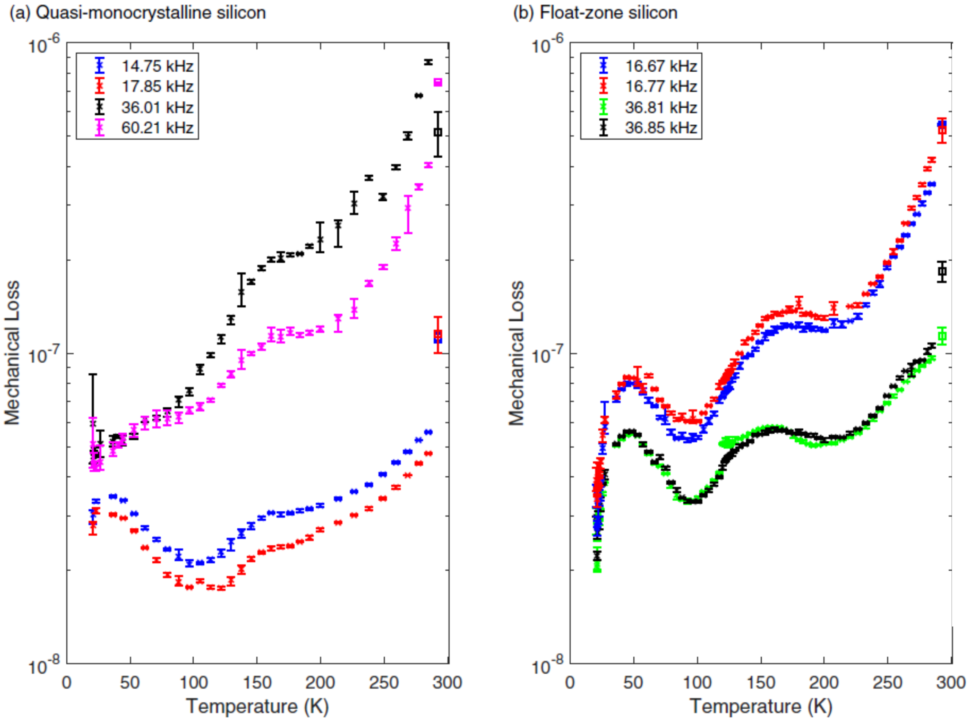
Degallaix et al., Optics Letters 38 (2013)

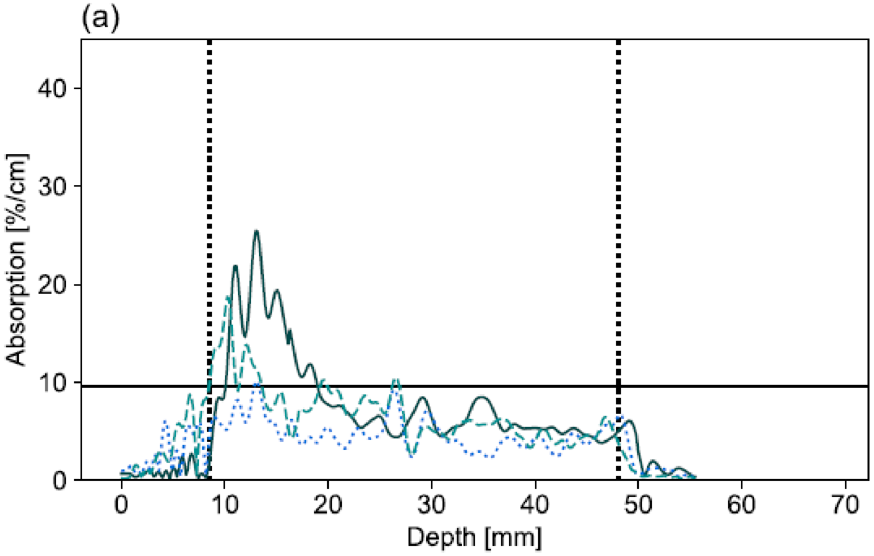
A. Markosyan, A. Bell LIGO-G1700480



Silicon mirrors for GW detectors

- Quasi-monocrystalline silicon grown by directional solidification
  - Can be produced in large sizes e.g. squares > 1 m
  - Cryogenic mechanical loss comparable to float zone
  - Test sample had high absorption, however doped feedstock used
  - Investigations into improving absorption required e.g. pure feedstock, alterations to growth process to reduce impurities
  - Growth likely to need optimised to ensure a large enough area is monocrystalline





[Bruckner et al. PRR 4 (2022)]

Silicon mirrors for GW detectors

- Broadly speaking: we can have large silicon, or we can have silicon with low optical absorption, but challenging (so far) to get both at once

- Option 1 – find a technique for making low optical absorption silicon in lager sizes that is economically viable for GW detectors (magnetically purified Czochralski shows some promise in principle)

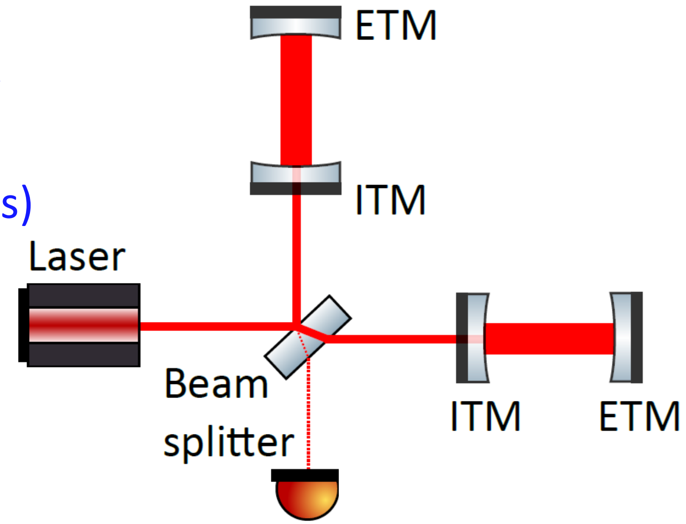
- Option 2 – construct composite test masses by bonding together pieces of low optical absorption silicon
    - Potential for excess thermal noise from bonds close to the laser beam
    - Potential for optical effects (scattering / distortion of wave fronts / absorption) due to trasmitting beam through bonds

- Option 3– can we exploit different requirements of ITMs and ETMs and use an ‘asymmetric test-mass‘ design?

Requirements for ITMs and ETMs

- Different absorption tolerances on the ITM and ETM, as the ITM transmits more laser power - e.g. for ET-LF
  - ITM transmits ≈ 30 W
  - ETM transmits ≈ 90 mW

(Assuming 18 kW circulating arm cavity power and standard ITM/ETM reflectivities)

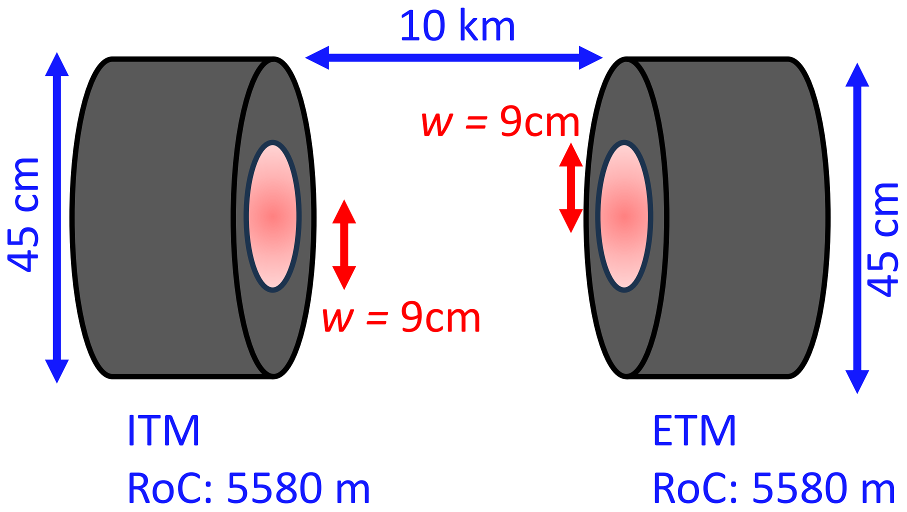


- So the ETM material can have a factor of 30 W/90 mW ≈ 300 higher optical absorption than ITM material, and absorb the same absolute laser power

- Only need low absorption material for the ITM

Asymmetric test-mass configuration

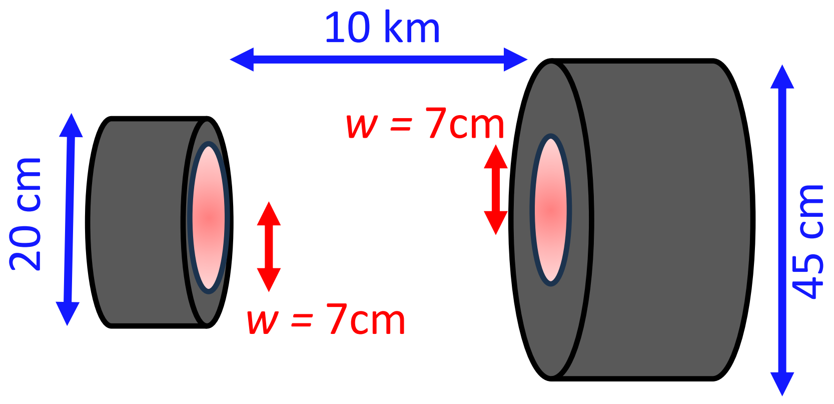
- Only need low absorption for ITM – can we use a small float zone mirror for ITM and only use a large mirror for the ETM?



ET arm configuration from Design Study

Asymmetric test-mass configuration

- Only need low absorption for ITM – can we use a small float zone mirror for ITM and only use a large mirror for the ETM?
- Beam size is limited by mirror size (scattering losses at edge) – want mirror diameter ≈2.5x beam diameter i.e. beam radius 4 cm for 20 cm mirror



ITM
RoC: R1
Float Zone

ETM
RoC: R1
Higher absorption material

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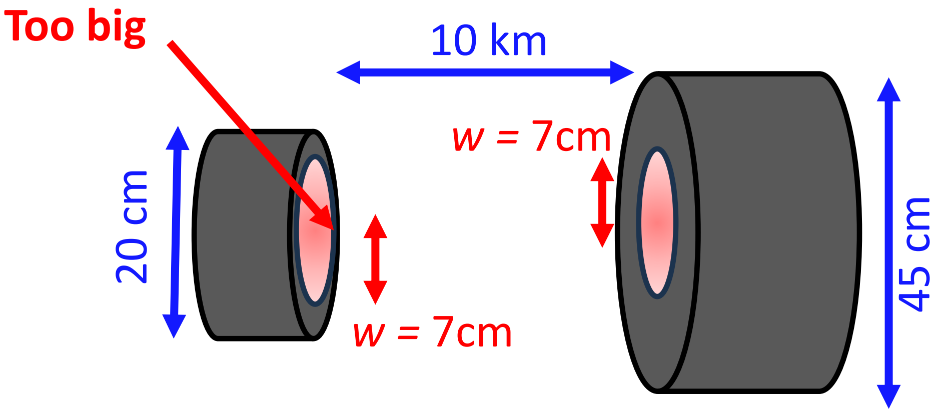

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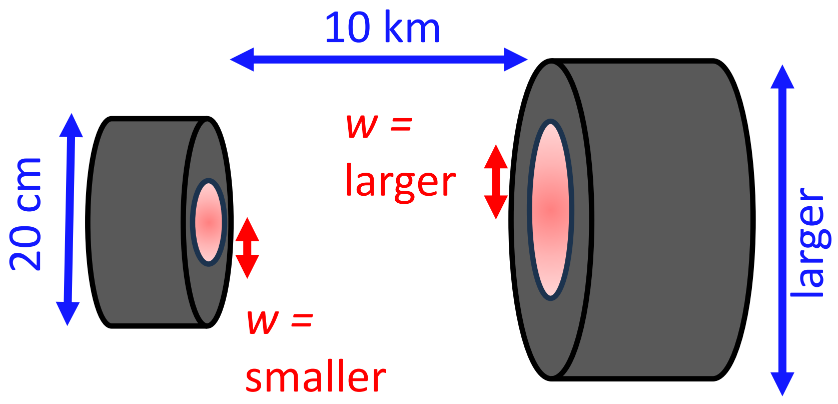
- Beam size is limited by mirror size (scattering losses at edge) – want mirror diameter ≈2.5x beam diameter i.e. beam radius 4 cm for 20 cm mirror
- But we can make beam smaller on the ITM – resulting in larger beam on ETM



ITM
RoC: R1
Float Zone

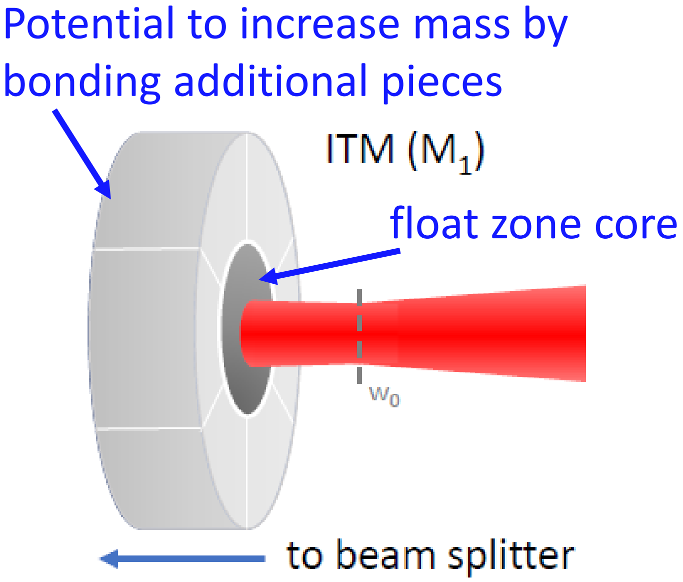
ETM
RoC: R2
Higher absorption material

Input test masses

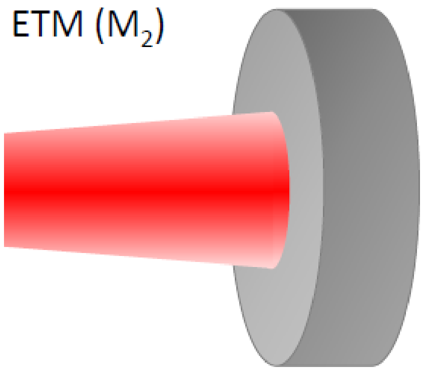
- ITM - use low absorbing float zone silicon, available (currently?) in diameters of ≈ 20 cm, rather than the ≈ 45 cm Design Study value
- Requires smaller beam to avoid excess scattering at edges of mirror
  - e.g. beam radius of ≈ 4 cm to maintain factor of 2.5 between beam diameter and mirror diameters

- Reduction in ITM mass not ideal (e.g. for radiation pressure noise)
  - Possibly solve by bonding pieces around 20 cm float zone core
  - Reducing potential issues with the bonds transmitting the laser beam in the "classical" composite mass case.

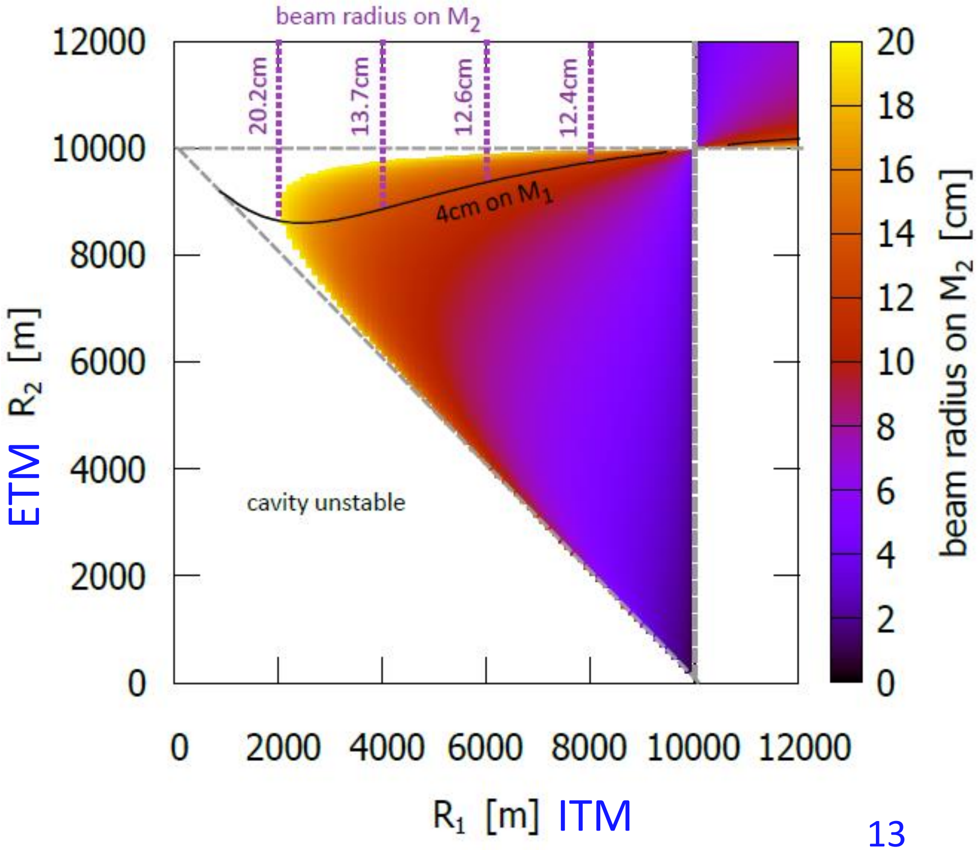
- Smaller beam will increase coating thermal noise – but more later….



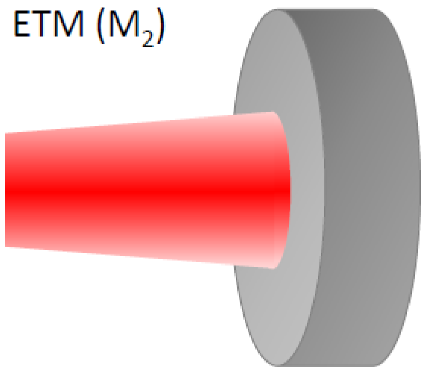
End test masses



- ETM – can use larger diameter silicon due to relaxed absorption requirement e.g. Czochralski / quasi-monocrystalline silicon
- Larger mirror allows larger laser beam – reducing the ETM coating thermal noise
- For a stable cavity with a 4 cm beam radius on the ITM (allowing use of float zone Si):
  - the minimum beam radius on the ETM is ≈ 12.5 cm
  - resulting in an ETM mirror diameter of ≈ 62.5 cm being required



End test masses



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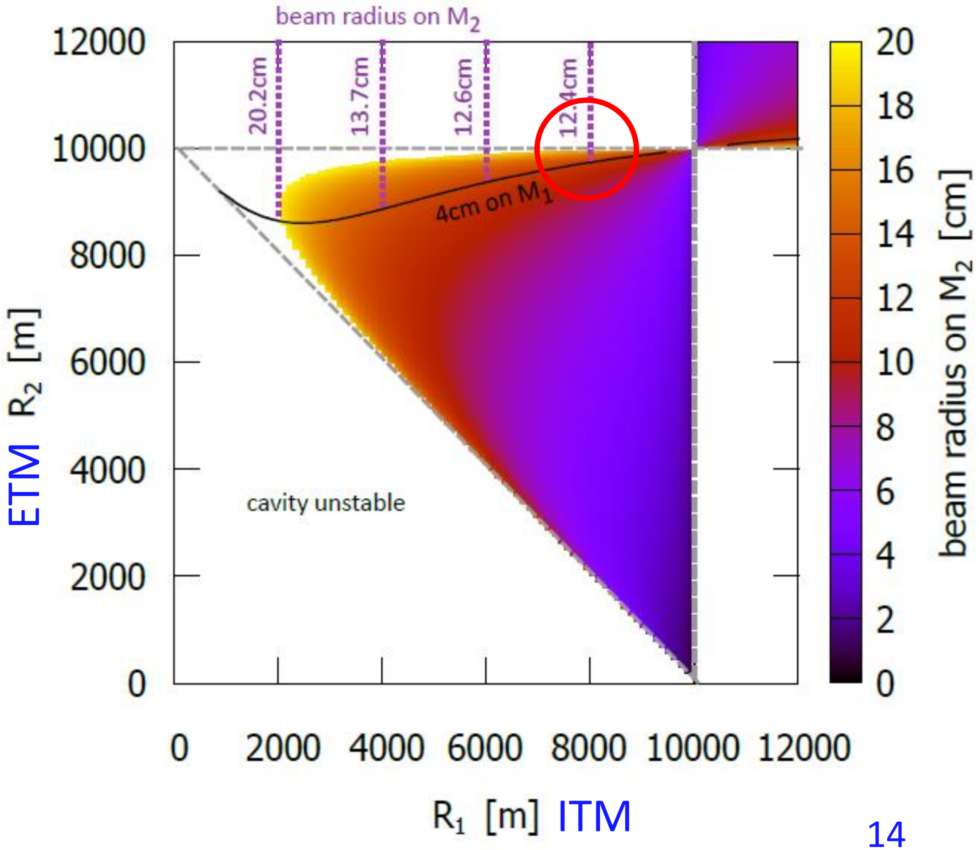
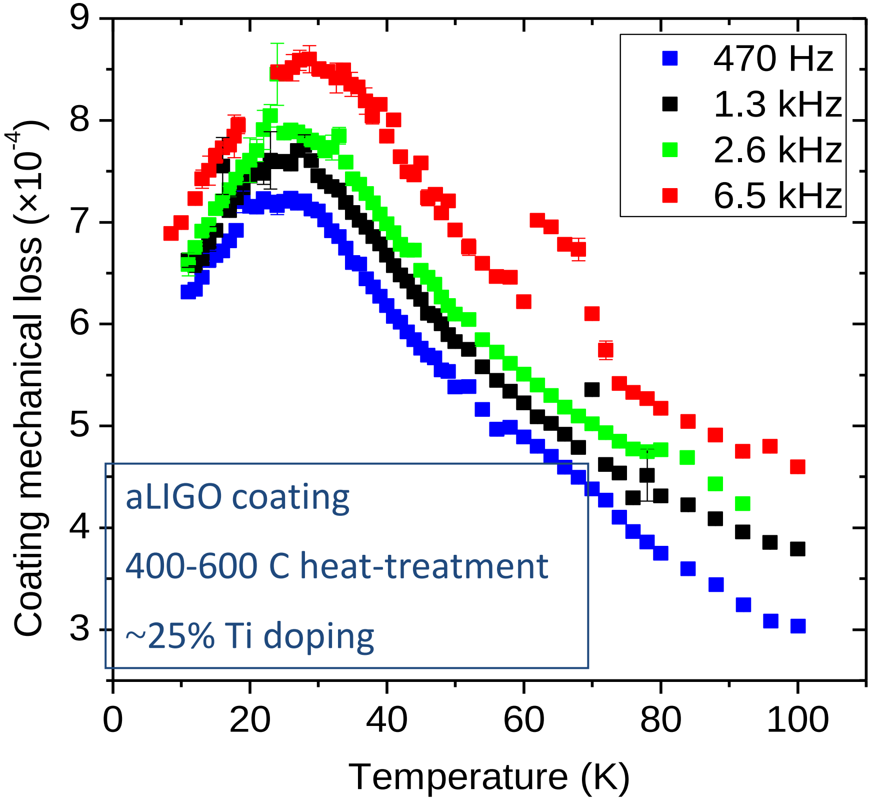


Coating thermal noise

- Coating thermal noise (CTN) reduces when cooling to cryogenic temperature
- For current aLIGO/Adv Virgo coating materials (SiO_2/Ti:Ta_2O_5) reduction partially offset by increase in cryogenic mechanical loss
- ET Design Study CTN target
  - $\lesssim 3.6\times10{-}21$ m/$Hz^{-1/2}$ at 10Hz
  - target is 2x lower than likely to be achievable using SiO_2/Ti:Ta_2O_5 coatings at 10 K (3x at 20 K)
  - assumed 9cm (radius) beams on ITM and ETM

$$x(f) = \sqrt{\frac{2k_BT}{\pi^2 f}\,\frac{d}{w^2}\,\phi\left(\frac{Y_{\rm coat}}{Y_{\rm sub}^2} + \frac{1}{Y_{\rm coat}}\right)}\,.$$



aLIGO coating

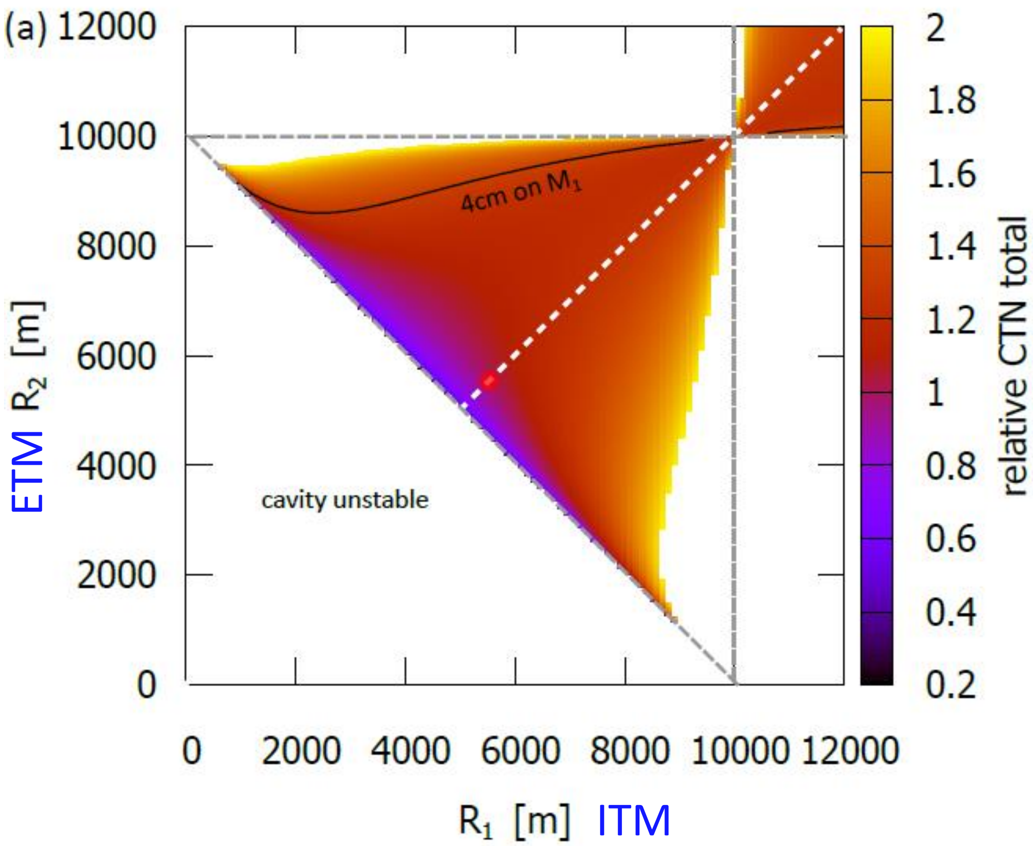
400-600 C heat-treatment

~25% Ti doping

M Granata et al Optics Letters 38 (2013)

Coating thermal noise optimisation 1

- ITM coatings less reflective → thinner → lower thermal noise
- CTN goes as $1/w^2$
- Red dot: ET Design Study case – 9 cm beam on both mirrors (5580 m RoC)
- White dashed line shows equal RoC on both mirrors
  - due to thicker ETM coating, slightly larger beam on ETM and smaler on ITM is favourable
  - aLIGO uses slightly asymmetric beams (smaller ITM, larger ETM); Virgo also considered/planning to use much larger beam on ETM



$$x(f) = \sqrt{\frac{2k_B T}{\pi^2 f}\frac{d}{w^2}\phi\left(\frac{Y_{\text{coat}}}{Y_{\text{sub}}^2} + \frac{1}{Y_{\text{coat}}}\right)}$$

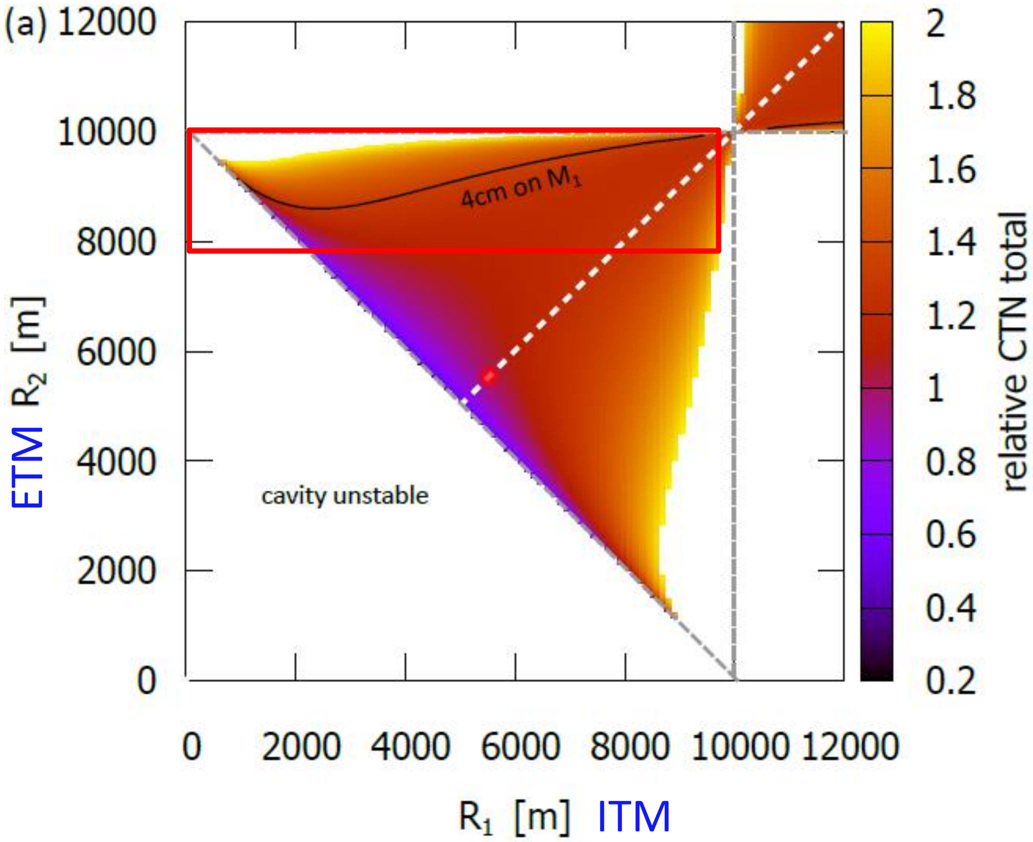
$$x_{\text{total}} = \sqrt{2 \times x_{\text{ETM}}^2 + 2 \times x_{\text{ITM}}^2}$$

Coating thermal noise optimisation 2

- Suggested configuration of 4 cm beam on 20 cm float zone ITM, while keeping ETM as small as possible, results in overall increase in CTN by ≈30%

- No solution with a 4 cm ITM beam that reduces CTN

- Increase in CTN may be acceptable if this configuration is the only viable way to solve the silicon size problem

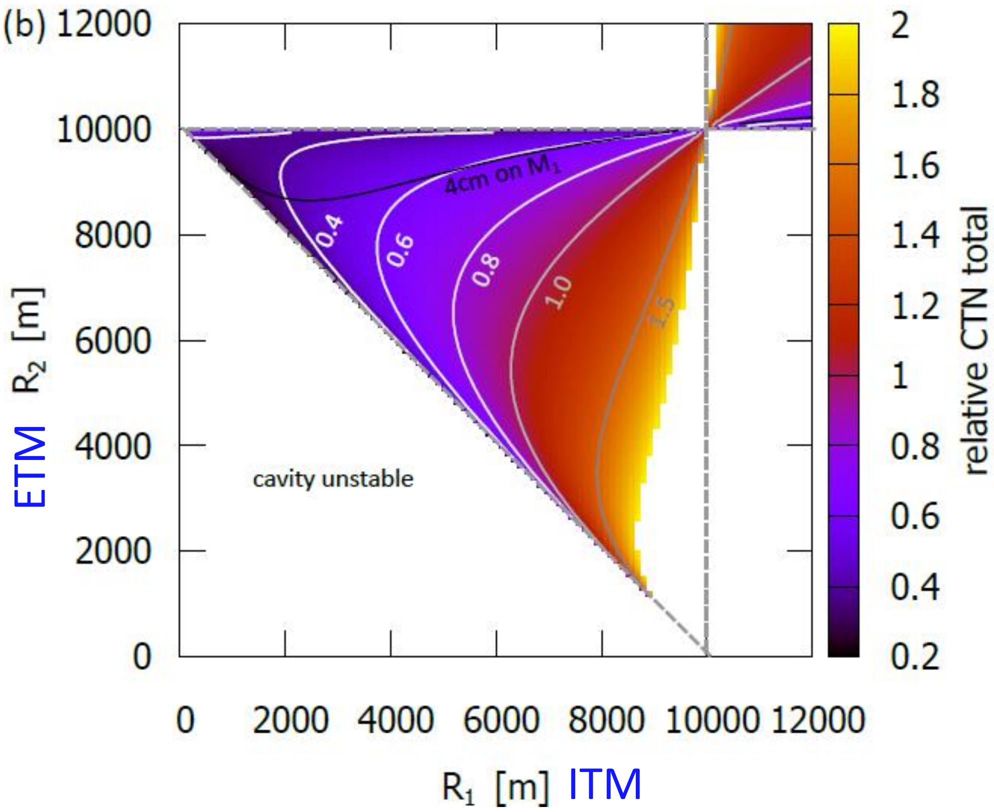


$$x(f) = \sqrt{\frac{2k_BT}{\pi^2 f}\frac{d}{w^2}\phi\left(\frac{Y_{\rm coat}}{Y_{\rm sub}^2}+\frac{1}{Y_{\rm coat}}\right)}$$

$$x_{\rm total} = \sqrt{2\times x_{\rm ETM}^2 + 2\times x_{\rm ITM}^2}$$

Coating thermal noise optimisation 3

- However, 20 cm ITM allows possibility of using AlGaAs coatings
  - Single crystalline MBE coatings
  - very low cryogenic loss (up to 100x lower than SiO_2/Ta_2O_5)
  - very low absorption
  - currently limited in size to 20 cm diameter due to availability of GaAs wafers as growth substrates

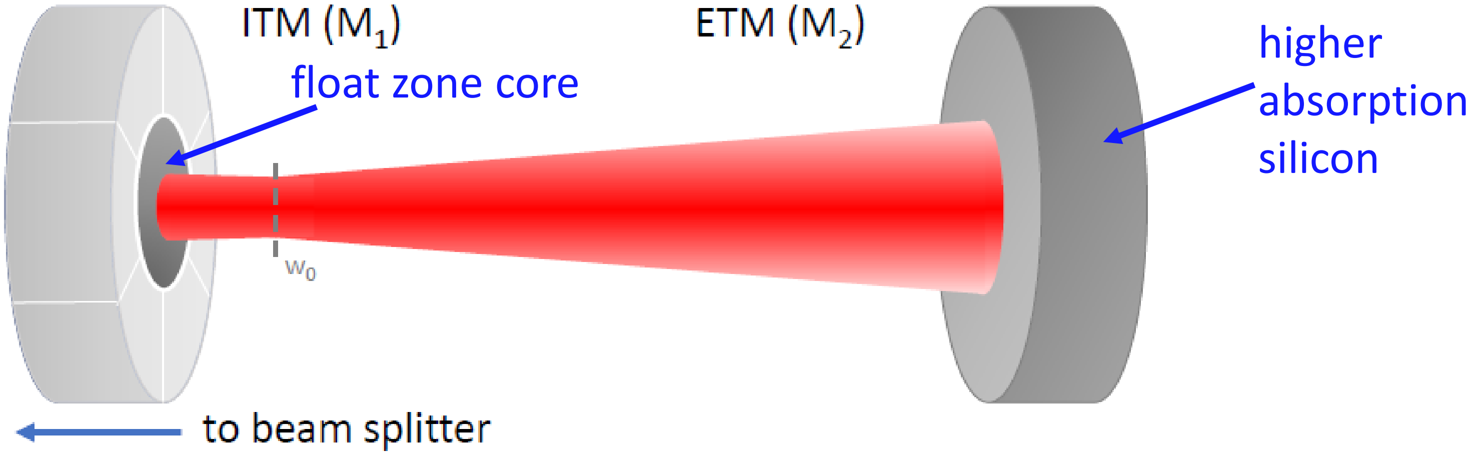


- Use of AlGaAs on ITM and a 4-material amorphous coating on ETM (Craig et al. PRL 122, 2019) gives significant CTN reduction with our proposed configuration (4 cm beam on 20 cm ITM) – lower than the ET Design Study CTN requirement

$$x(f) = \sqrt{\frac{2k_B T}{\pi^2 f}\frac{d}{w^2}\phi\left(\frac{Y_{\text{coat}}}{Y_{\text{sub}}^2} + \frac{1}{Y_{\text{coat}}}\right)}$$

$$x_{\text{total}} = \sqrt{2 \times x_{\text{ETM}}^2 + 2 \times x_{\text{ITM}}^2}$$

Summary



- Investigated using different types of silicon and very different beam sizes for the ITMs and ETMs
- Based on 20 cm diamater float zone, a stable configuration that minimises the size of the ETM is:
  - 20 cm diameter float zone Si ITM with 4 cm beam radius
  - 62.5 cm diameter ETM, higher absorbing Si, 12.5 cm beam radius
  - Possiblity to increase mass of ITM via bonding a composite mass, but with the beam ‘entirely‘ contained on the 20 cm float zone core
- Small ITM beam would allow the use of 20 cm AlGaAs ITM coatings, potentially allowing the ET-LF CTN goal to be surpassed

Challenges and open questions

- How close to the cavity stability criterion can we go in practice?
- Bonding to increase mass of ITM – what bonding configurations are possible? What is the thermal noise effect of bonds located outside the nominal laser beam radius?
- AlGaAs coatings - in principle can work up to 20 cm but (to my current knowledge) 20 cm AlGaAs substrate transfer to silicon has not yet been demonstrated
- Can quasi-monocrystalline silicon absorption be lowered enough for use as an ETM? If not, can we get big enough ETM, with low enough absorption using some other method?